LCA Discussions

Efficient Information Visualization in LCA

Introduction and Overview

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Abstract

Background, Goal and Scope. A complete life cycle assessment (LCA) always requires several itemizations of goal/scope definitions, inventory analysis and impact analysis. This requires the retrieval and collection of inventory information on all processes with which a product or any part of it comes into either direct or indirect contact. As a result, the data required for LCA is vast, uncertain and, therefore, complex. Up until now, unfortunately, and as far as the authors are aware, there has not been much computer-assisted aid available from any of the systems currently used in either academia or industry to support any life cycle (LC) related data representation, other than the traditional methods of tables, xy-graphs, bar charts, pie charts and various 3-D variants of those which are difficult for humans to interpret.

Main Features. Benefiting from the synergy of latest developments in both visualization techniques and computer technology, the authors are able to introduce a new information representation approach based on glyphs. These exploit the human perceptual capability for distinguishing spatial structures and shapes presented in different colors and textures. Within this approach, issues of representing life cycle related information at a glance, filtering out data so as to reduce the information load, and representation of data features, such as uncertainty and estimated errors, are targeted.

Results. Advanced information visualization, the process which transforms and maps data to a visual representation, employs the glyphs rendered here to create abstract representations of multi-dimensional data sets. Different parameters describing spatial, geometrical and retinal properties of such glyphs, and defining their position, orientation, shape, color, etc., can be used to encode more information in a comprehensible format, thus allowing multiple values to be encoded in those glyph parameters. The natural function of glyphs, linking (mapped) data within a known context with the attributes that in turn control their visualization, is believed capable of providing sufficient functionality to interactively support designers and LCA experts performing life cycle inventory (LCI) information analysis so that they can operate faster and more efficiently than at present.

Conclusions. Within this paper, the first of a small series on efficient information visualization in LCA, the motivation for and essential basic principles of the approach are introduced and discussed. With this technique, the essential characteristics of data, relationships, patterns, trends, etc. can be represented in a much better structured and compact manner, thus rendering them clearer and more meaningful. It is hoped that a continuing interest in this work combined with an improved collaboration with industrial partners will eventually provide the grounds for translating this novel approach into an efficient and reliable tool enhancing applied LCA in practice on a broader base.

Outlook. More technical details of the approach and its implementation will be introduced and discussed in the following papers, and examples will be offered demonstrating its application and first experimental translation into practice.

Keywords: Glyph rendering, information visualization, life cycle assessment, life cycle inventory, life cycle data set mapping, multi-dimensional information space

1 Background, Goal and Scope

As a result of the increased use of information technology (IT), the amount of data stored in the world is doubling approximately every 20 months. Within individual disciplines such as product design and development, holistic approaches like life cycle management and life cycle modeling (LCM) are being adopted, and include complex activities such as life cycle assessment (LCA). Here, experts may have to cope with in excess of 10^5 numerical data elements (Bretz 1998) while compiling the life cycle inventory (LCI) of a product. However, data do not become useful until some of the information they carry is extracted, and, most importantly, represented in a way humans can both recognize efficiently and understand. The information representation techniques of most systems are still based on traditional 2D information spaces, and fail to capitalize on the ability of the human perception system to recognize and interpret multi-dimensional information spaces. In particular, the application of visualization systems which transform numerical data into pictures in which structures of interest in the data become perceptually apparent, is still the exception rather than common practice.

This paper is the first of a planned short series on efficient information visualization in LCA. It introduces the basic concept and some fundamental principles of a novel approach employing glyph-based visualization techniques for advanced interactive multi-dimensional visualization of LCA-related information. It offers a selective minimal background to computational geometry and visualization relevant to the scope of this paper, and discusses motivation and the essentials of funding and approach. Hopefully, these basic principles, with illustrated figures will convey the essentials of the approach, and encourage the reader to progress to the next following papers, in which technical details of the approach and its implementation will be discussed and examples will be given demonstrating its application and translation into practice.

2 Information Visualization and LCA

Information visualization is the process which transforms and maps data to a visual representation. At their usually low level of representation, (raw) data are often hard to interpret. On the other hand, visual representations are easy for humans to understand due to our perceptual capabilities for distinguishing spatial structures and shapes presented in different colors and textures.

2.1 Approaches and related work

The use of icons and glyphs to create abstract visualizations of multi-dimensional data sets is based on those human perceptual capabilities. Different parameters describing spatial, geometrical and retinal properties of such icons or glyphs, and defining their position, orientation, shape, color, etc., are commonly used to encode more information in a comprehensible format, allowing multiple values to be encoded in those glyph parameters (Ribarsky et al. 1994, Post et al. 1995). The visualization of icons and glyphs is based on the concept of marks such as points, lines, areas, surfaces and volumes and their graphical properties (Bertin 1983, Mackinlay 1986). Early work in logic and semiotics (Feibleman 1969, Chang 1989) had already offered attempts to relate the meaning of icons to the properties of their graphical representation. The first technical applications to exploit the effectiveness of iconic and glyph-based visualization due to the human eye-brain system's ability to discern finely resolved spatial relationships and differences in color, texture and shape, appeared in the field of engineering mechanics (Ellson and Cox 1988, Haber and McNabb 1990). Next came glyph-based visualization displaying the properties of vector fields (Globus et al. 1991, Walsum and Post 1994) and vortex tubes extracted from flow fields (Villasenor and Vincent 1992) – to mention only two examples – and this was followed by the development of frameworks and systems designed to generate and interactively investigate icon and glyph-based visualization (Ribarsky 1994, Post et al. 1995, Ebert et al. 2000). Further applications successfully employing information visualization in fields other than those mentioned above, such as (English) text and program analysis, internet web page navigation, display of complex graphs and analysis of large telecommunication data sets, can be found in (Eick et al. 1992, Rohrer et al. 1998, Cugini and Scholtz 1999, Abello and Korn 2000, Koutsofios et al. 2000). Work on information visualization taxonomy and the systematic analysis of point designs in this field, accompanied by numerous examples and a well-compiled list of reference literature, can be found in (Chuah and Roth 1996, Card and Mackinlay 1997, Card et al. 1999).

2.2 Problems and scope

A 'complete' LCA always requires several itemizations of goal/scope definitions, inventory analysis, impact analysis and the interpretation of these. As this leads rapidly to a vast amount of data that has to be stored, structured and analyzed (Otto et al. 2001a,b), the necessity of providing computerized tools to support a human expert becomes apparent beyond any doubt.

Especially in the stage between inventory analysis and impact assessment, the expert needs a considerable amount of (visual) aid to efficiently recognize multi-dimensional LCI-related data sets and quickly interpret relationships between given product design parameters and their impact on each life cycle phase, in regard to the design solution being investigated. Up to now, unfortunately, as far as the authors are aware, there has not been much computer-assisted aid available from any of the systems currently used to support any LCI-relevant or LCA-related data representation, other than value (nominal, ordered, quantitative) based tables, 2D diagrams and charts.

The purpose of the work described in this series of papers is to provide an initial framework and an experimental test bed to demonstrate and analyze the generation and use of rendered glyphs, the attributes of which are controlled by a selected set of mapped LCA-related information. The natural function of glyphs, linking (mapped) data within a known context with the attributes that in turn control their visualization, is believed capable of providing sufficient functionality to interactively support designers and LCA experts performing LCI information analysis so that they can operate faster and more efficiently than at present.

3 Background to Concepts and Structures Used

3.1 Basic notation

The basic notion of a set should be familiar, along with the basic operations. The set of Boolean truth values is denoted by **B**. Natural numbers are denoted by **N** and real numbers are denoted by **R**. In the theory of functions and mappings, a domain is the set of argument values for which a function or map is defined. A function or map is a correspondence by which each element of a given set has associated with it one or more elements of a second set. In the following, the standard notation $f : X \rightarrow Y$ will be used to indicate that f is a function or mapping with a domain X and codomain Y, that is for every $x \in X$, $f(x) \in Y$. The cross product of two elements x_m and x_n is denoted by $x_m \times x_n$.

To remain consistent with the notation of modern mathematics, where superincumbent bars and arrows are omitted when writing vectors, they are denoted by single small letters in boldface such as $\mathbf{x}$. Matrices are usually denoted by single capital letters A, B, etc. The transpose of the $m \times n$ matrix A, denoted by A^T, is the $n \times m$ matrix, the rows of which are given by the columns of A. Equivalently, the columns of A^T are given by the rows of A.

Further details can be found in (Schneider and Barker 1989, Kaye and Wilson 1998).

3.2 Point spaces, ellipsoids and glyphs

The vector space or linear space of n-tuples of real numbers is usually denoted as $\mathbf{R}^n$, with one member of special interest, the $\mathbf{R}^3$, the linear space of 3D vectors. The space of our normal experience is called Euclidean three-space, denoted as $\mathbf{E}^3$, which is the point space of triples of numbers. Vectors in the $\mathbf{R}^3$ correspond with directed lines in $\mathbf{E}^3$ from one point (the blunt end of the vector arrow) to another point (the sharp end of the vector arrow). All points p_n in $\mathbf{E}^3$ are represented by coordinates $p_n = (x_n, y_n, z_n)$. The point corresponding to (0,0,0) is termed the origin, and we speak of the point (x_n, y_n, z_n), when we actually mean the point which corresponds to this ordered triple. Remember that a curve is a continuous image of an interval and a surface is a continuous image of a product of intervals.

Ellipsoids are a class of special quadratic surfaces representing a closed, non-empty singular object. They are defined by the coordinates of their center and the length of their three half-axes. There are two families of parallel circular cross sections in every ellipsoid. However, the two coincide for spheroids. As a result, a spheroid has only two distinct axis lengths. A sphere is an ellipsoid where all three half-axes are equal. Due to the central role of ellipsoids regarding the geometric structure of glyphs, a more detailed review shall be given as provided in the appendix.

In general, the basic meaning of the term icon or glyph is a pictorial representation sharing one or more properties with the item which it represents. Basically, glyphs are graphical objects whose attributes are bound to data. Those attributes which describe the degree of freedom of a glyph are actually a combination of different types of parameters describing geometric, spatial and retinal properties. As already mentioned, the advantage of using glyph-based data visualization is based on human perceptual abilities. However, perception of these visualization attributes is not yet understood equally (Parker et al. 1992, Byrne 1997, Davis 1999). Especially 3D shape perception, with the pre-attentive ability of the human visual system to discern shape, is still a challenging field. Here, one of the most difficult problems is to find the best design for meaningful glyph shapes, so that they are able to convey structure and changes in associated data values in a comprehensible manner. More details on glyphs and this subject can be found in (Ribarsky et al. 1994, Post et al. 1995, Ebert et al. 2000).

4 The Visualization Method

4.1 Outline

Techniques in visualization provide tools for obtaining information quickly and efficiently from data. These may range from basic presentation techniques, merely displaying the data in a clear manner, to sophisticated techniques capable of automatically extracting, mapping and displaying an information set. Within the scope of the work presented, the focus will be on the use of the latter, employing the particular technique of glyphs, acting as symbolic representations displaying the essential characteristics of a data domain to which they are linked. This visualization concept replaces original data by a carefully designed symbolic, interactive display, featuring a structured and compact, and hence clearer and more meaningful representation. As mentioned above, these well-known advantages of glyph-based information visualization, already experienced in other technical applications, will now be investigated and applied to LCA. Before we can proceed to this, however, we must have a proper understanding of the basic requirements of the data structure of LCA-related information. This will guide us in the design of a glyph-based, multi-dimensional information space which has sufficient visualization functionality in regard to the associated reference domain.

4.2 Basic structures and requirements

In LCA, there are two principal types of information that are predominantly used for analysis.

First, there is information on low-level data amounts, involving complex structure, already representing sets of summarized data. Examples are environmental impact class values such as global warming potential in carbon dioxide equivalents over a 20-year period, or summary indicator values such as weighted and normalized single indicative measures, both derived from environmental impact analysis.

Second, there is information with less complex structure, on a more data intensive inventory level. Examples are material and energy inventory, such as mass of steel or electric energy requirements, or environmental items such as carbon monoxide levels. Information within such inventories is usually classified within comprehensive lists into energy, material and environmental items. Most entries are related to one particular entity within one class (data type) and consist of an amount either required or produced (data value, i.e. quantity), a degree of uncertainty or estimated data error (data quality), and further references to particular life cycle phases, products, assemblies, parts, etc. (data context). A structure needs to be developed to support the identification of the context in which given information needs to be interpreted, and to help answer questions about the interconnection between and relative importance of life cycle phases, and about the interconnection between and relative importance of parts and products with respect to their function and possible impact on the life cycle.

4.3 Approach

The basic idea of glyph-based scientific information visualization can be described using a process model, based on the visualization pipeline described in (Haber and McNabb 1990). This relates individual activities, such as data generation and attribute calculation, to entities such as field data and attribute sets. However, an alternative method is to provide an overview of the visualization process by simultaneously looking at both the original data space and the information visualization space from different viewpoints. In this paper, the emphasis will be placed on this latter approach. Placing the viewpoints in an ascending level of abstraction, one can look at concrete entities represented by actual instances, or at extracted properties and attributes of interest, or at formal structures and mappings, as shown in **Fig. 1**. Each viewpoint has its own important features most suited to a particular task. For example, specifications for consistent data structures and algorithms from which programs are to be derived later, can be seen much better at the abstract level of formal structures than by considering entity properties, or even concrete entities, described in a natural language. During the course of this series of discussions, when issues become more complex and require concise and less ambiguous means of description, we will literally work our way up from the bottom to the top.

In mathematics, a domain is referred to as the set of argument values for which a function or map is defined. In general, a domain refers to the description of permitted values of an attribute. The physical description is a set of values

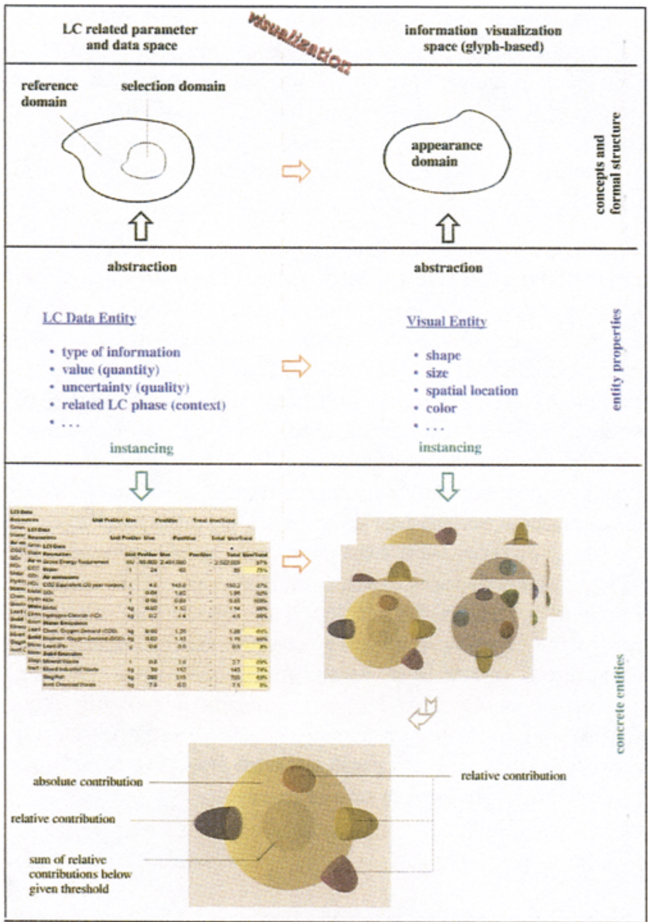

Fig. 1: The LC data entity space and the information visualization space at different levels of abstraction

which the attribute can take, and the semantic, or logical, description is the meaning of the attribute. Relating this to the scope of LCA-related information visualization, three basic domains can be identified, as shown in Fig. 1. First, the domain which contains all sets of data that are of interest and subject to eventual visualization. Second, particular data sets of the reference domain that are associated with current mappings as input to generate visualization of a chosen scenario defining the settings of all parameters and contexts used before calculations take place. Third, the appearance domain, a space in which the glyph object exists. Note that this space should not be confused with the display screen of a computer or the Euclidean three-space, since the appearance of glyphs is not limited to those, but is defined and represented by a combination of spatial, geometric and retinal properties. Even acoustics could be added, though the details on how to integrate acoustics into the framework are not clearly defined as yet.

Within the framework developed, the structure of the central visual entity of the LCA-related multi-dimensional information visualization space, the OM-glyph (an advanced interactive glyph developed by and named after the authors, see Otto and Mueller 2002), has been designed as outlined in the next paragraph. This design aims to accommodate the basic data and information structure requirements as mentioned above. Note, that details are presented here on an informal basis in order to keep this section transparent and easy to read. A more formal discussion, including additional detail, will be found in the following papers of this series.

Due to its ergonomic shape and non-complex geometry, together with its being able to accommodate a reasonable number of control parameters, a particular quadratic surface in the form of a triaxial ellipsoid has been chosen as the basic shape component of the OM-glyph. A complete glyph consists of a center, which is represented by a sphere, to which general ellipsoids are attached. The origin of each glyph is the origin of the sphere in the center. Each ellipsoid attached is spatially arranged such that its half axis b is colinear with the vector that emanates from the origin of the sphere in the center of the glyph while pointing in the direction of the origin of the ellipsoid attached. This structure forms an ellipsoid cluster with spatially intersecting components, each aligned towards the origin of the glyph (see examples in Fig. 1). Since the glyph center is represented by a sphere, each ellipsoid attached is equidistant from the glyph origin, as measured at the intersection of surfaces. Since the OM-glyph is an interactive 3D object, which can be translated, rotated, etc. on a computer, the information visualized needs to be visible from all viewing angles, though perhaps varying in detail quality. To achieve this goal, all individual glyph components support control over opacity and transparency to avoid the total obscuring of small glyphs by large. In this way, all information visualized within one rendered image is always visible to the user, regardless of the graphical viewpoint and spatial arrangement used. To provide a user controlled tool to assist in the reduction of less significant detail, while relating an order of magnitude, each OM-glyph comes with a glyph filter function denoted by $\psi: \mathbf{R}^+ \rightarrow (\mathbf{B} \times \mathbf{R}^+)$, which maps single parameter values to adjusted (parameter) values with a filter label attached, basically preventing explicit visualization of LC data entities with values below a user given (filter) threshold.

In the following paragraph, some basic mappings between properties of LC data entities and properties of OM-glyphs, describing relationships of different forms of information representation, are introduced and discussed. The type or class of an LC data entity is represented by a color. Each user-defined set of colors for different types is associated with respective entity classes within a real set of LC inventories. Colors may encode energy forms, materials, environmental items, LC phases or individual parts or assemblies of a product. To finely adjust each set of user defined colors, OM-glyphs, besides the basic color information, support additional control over the level of saturation and brightness. For example, within the enlarged OM-glyph shown in Fig. 1, the life cycle phase was assigned a dark yellow (central sphere), while environmental items which were produced (contributors) in this particular life cycle phase, such as carbon dioxide, sulfur oxides, sodium oxides and hydrogen oxides, were assigned dark blue, brownish red, dark greenish yellow and dark magenta, respectively.

The degree of contribution of an LC data entity, i.e. the quantity of a material required or of an environmental item produced, is represented by the size of an individual ellipsoid within a glyph. The visualization result can be controlled by employing a surface-based or a volume-based mapping, either implicit or explicit. In the case of an implicit mapping, the absolute amount $|cn_i|$ of a contribution $cn_i \varepsilon \mathbf{R}$ is set in relation to parameters a, b, and c, specifying either the surface or volume of an ellipsoid (cf. Equation 9 and Equation 10). The relationship can be described using a matrix B with linear terms bmn as coefficients and a vector $\boldsymbol{x} \varepsilon \mathbf{R}^3$ containing the half-axes values of the sphere in the center of the glyph to which the ellipsoid is attached, as shown in Equation 1.

$$[a,b,c]^T = Bx^T \qquad (1)$$

In the case of explicit mappings, the absolute amount of a contribution $|cn_i|$ is fixed in the relationship using a linear term $b(t)$, eventually parameterized to either the surface S or the volume V of the ellipsoid as shown in Equation 2 and Equation 3.

$$S = b(t)\ |cn_i| \qquad (2)$$

$$V = b(t)\ |cn_i| \qquad (3)$$

To achieve a better spatial balance among all glyph components, and also to improve their overall appearance, those mappings can be further adjusted by adding normalization and scaling operations, as is done for OM-glyphs, before rendering. Basically, there are three types of contribution visualized within one OM-glyph. The first is the relative contribution of LC data entities in relation to that which the glyph represents. In the example in Fig. 1, this would be the size of the ellipsoids representing the (relative) contributions of environmental items such as carbon dioxide, sulfur oxides, etc. that are produced in the 'use' life cycle phase. The second is the absolute sum of all LC data entities associated with the glyph. In the example in Fig. 1, this would be the size of the sphere in the center of the glyph. The third is the sum of all contributions below a threshold value (see glyph filter function introduced earlier). In the example this would be the size of the small inner sphere, located at the center of the glyph.

Data quality and related degrees of uncertainty in LC data entities, together with estimated data errors, are visually represented within OM-glyphs as system-controlled shape distortions resulting in spheroids appearing instead of ellipsoids as glyph components. Basically two types of spheroids are used: oblate spheroids and prolate spheroids (see Fig. 3 and 4, Appendix), depending on whether calculated average values of contributions are closer to an upper limit or to a lower limit. More details on this advanced feature of OM-glyphs, together with examples, will be given in a later paper.

The context of LC data entities is represented within OM-glyphs in several different basic and advanced structures, allowing the simultaneous visualization of various contexts and viewpoints within one image. Context is important not only to elevate (raw) data to information, but within all analysis intensive tasks such as LCA, to support interpretation of information and the relationships, patterns, trends, etc. contained therein. Therefore, visual representation of this property has been given much consideration in the design of the OM-glyphs. Basic context relationships linking an energy form, material or environmental item to a life cycle phase, as is common in standard LCI tables (see, for example, the tables in Fig. 1), are represented using basic spatial and geometric relationships among glyph components and their properties, as already introduced. Since the sets of LC data entities selected for visualization (see selection domain in Fig. 1, upper section) can be exchanged and re-linked on a dynamic base, information can be visualized using different context settings. For example, the enlarged glyph shown in Fig. 1 was used to visualize the (relative) contributions of environmental items of one part of a product related to a particular life cycle phase. By modifying the sets of related LC data entities according to the context selected, this visualization scenario can also be used to represent the same type of information with re-calculated data values for other parts, or for the entire product, or for different life cycle phases for each of these. By using different sets of associated LC data entities, one can model any context combination and visualize data related to it within different glyphs. To increase not only basic context combinations, but the number of different contexts used to visualize LC-related information within one combination, higher orders of OM-glyph structures, such as glyph matrices and spherical glyph clusters, can be used. They will be introduced in a later paper together with examples, to show how LC-related information, usually presented in table form or in traditional charts, can be represented at an advanced level using a multi-dimensional information visualization space.

5 Conclusions

Within the first paper of this small series on efficient information visualization in LCA, a novel approach has been presented and discussed briefly. This innovative technique involves the introduction of OM-glyph based information visualization. A short background was given, mentioning related work, and the motivation for and basic principles of the new technique were then introduced. With this technique, the essential characteristics of data, relationships, patterns, trends, etc. can be represented in a much better structured and compact manner, rendering them clearer and more meaningful. It is hoped that a continuing interest in this work combined with an improved collaboration with industrial partners will eventually provide grounds for translating this novel approach into an efficient and reliable tool enhancing applied LCA in practice on a broader base.

6 Recommendation and Outlook

To ensure that the work presented was accessible to a broad audience of experts from different disciplines in both academia and industry, concepts and structures were presented on an

informal basis, offering a transparent and easy to understand synopsis. Both the topic and the approach introduced are of an interdisciplinary nature, requiring background knowledge in various scientific and engineering fields. Therefore, in case of need, references to supplementary literature on basic background have been included in the list given.

Hoping to have stimulated the interest of the reader by this initial overview, the authors will proceed to more advanced properties and structures of OM-glyphs in a following paper and will offer examples using data from actual industrial products. A third paper will then provide a deeper insight into the visualization framework which has been developed, and will also contain more technical details presented in a more abstract and formal manner together with an example of a full application using data from actual industrial products.

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Discussion contributions from the LCA community will be well appreciated by the authors.

Appendix

A general quadratic surface defines point sets with coordinates that fulfill the equation

$$xAx^T + 2ax^T + a = 0 \quad (4)$$

with $x = (x,y,z)$, $a = (a_1,a_2,a_3)$ and A the symmetric coefficient matrix with $a_{nm} = a_{mn}$.

A special quadratic surface with a symmetry point representing a non-empty singular object described using Cartesian coordinates by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad (5)$$

where the half-axes, sometimes also called semi-axes, are of length a, b, and c, is called a general ellipsoid or triaxial ellipsoid (**Fig. 2**). An equivalent description in the parametric form generally used in algorithm specifications and programming is given by the following equation set

$$x = a\cos(\alpha)\sin(\beta) \quad (6)$$

$$y = b\sin(\alpha)\sin(\beta) \quad (7)$$

$$z = c\cos(\beta) \quad (8)$$

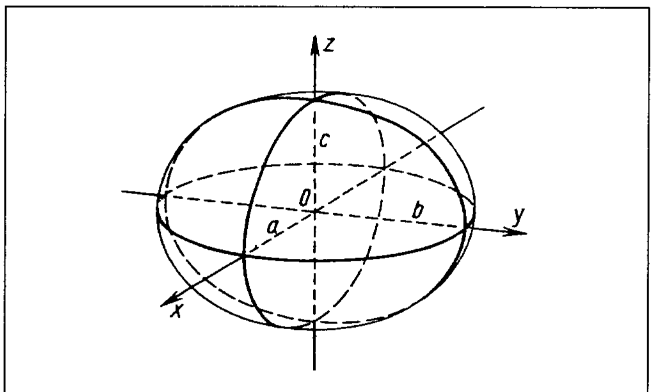

Fig. 2: General ellipsoid

for $\alpha \in [0,2\pi]$ and $\beta \in [0,\pi]$. Different sets of parametric equations using vector notation or Mercator parameterization may also be used to describe such geometric structures. If the lengths of two axes of such an ellipsoid are the same, the structure is called a spheroid. Depending on the relationship of the half-axes, i.e. whether $c < a$ or $c > a$ it is called an oblate spheroid (**Fig. 3**) or a prolate spheroid (**Fig. 4**). When all three half-axes are equal, i.e. $a = b = c$, the spheroid is called a sphere.

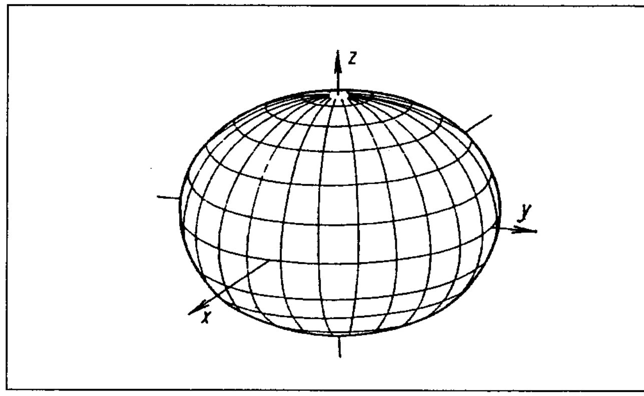

Fig. 3: Oblate spheroid

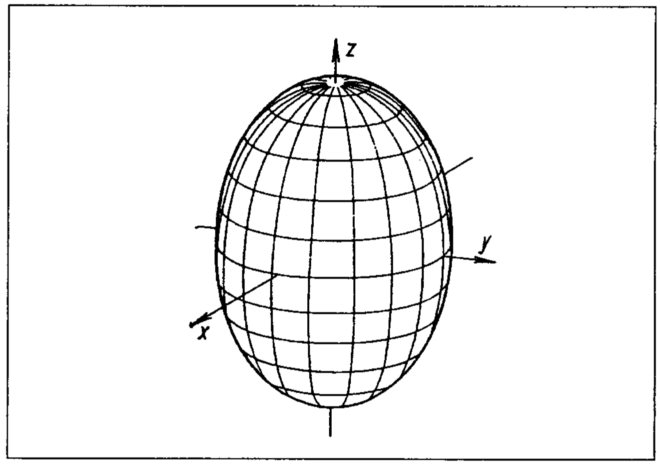

Fig. 4: Prolate spheroid

The volume V of a general ellipsoid can be described directly using the length of the half-axes by

$$V = \frac{4}{3}\pi abc \quad (9)$$

The surface area S of a general ellipsoid containing a complete elliptical integral $E(\alpha)$ of the second kind with Jacobi elliptic functions can be described by

$$S = 2\pi c^2 + \frac{2\pi b}{\sqrt{a^2-c^2}}[(a^2-c^2)E(\alpha)+c^2\alpha] \quad (10)$$

Further details of these formulae and additional information on this subject can be found in (Bowman 1961, Berg et al. 1997, Harris and Stocker 1998).

About Dr. Harald E. Otto, University of Tokyo

Studied mathematics, computer science, cognitive science and philosophy in Darmstadt, Frankfurt and Cambridge. Holds a diploma degree in computer science and mathematics from Darmstadt University and a CAD/CAM related Ph.D. from Tokyo University. He was active in the fields of geometric modeling, system design, formal language design, product modeling and product development at the Center for Interactive Graphics Systems (ZGDV, Germany), Philips Product Research and Development Center (PRDC, Germany), German National Research Center for Information Technology (GMD, Germany) and the Research Center for Advanced Science and Technology (RCAST, Japan). Currently active in product and process modeling, CAD data exchange, multi-dimensional information visualization and product life cycle modeling at the University of Tokyo.